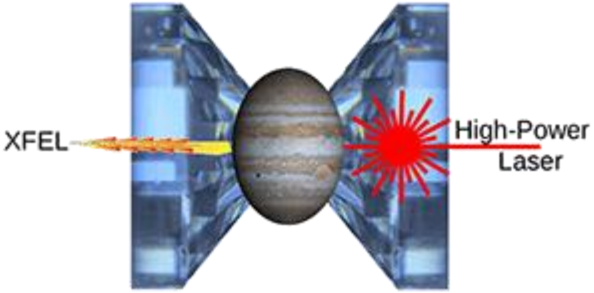

Investigating exoplanet interiors from transit light curves

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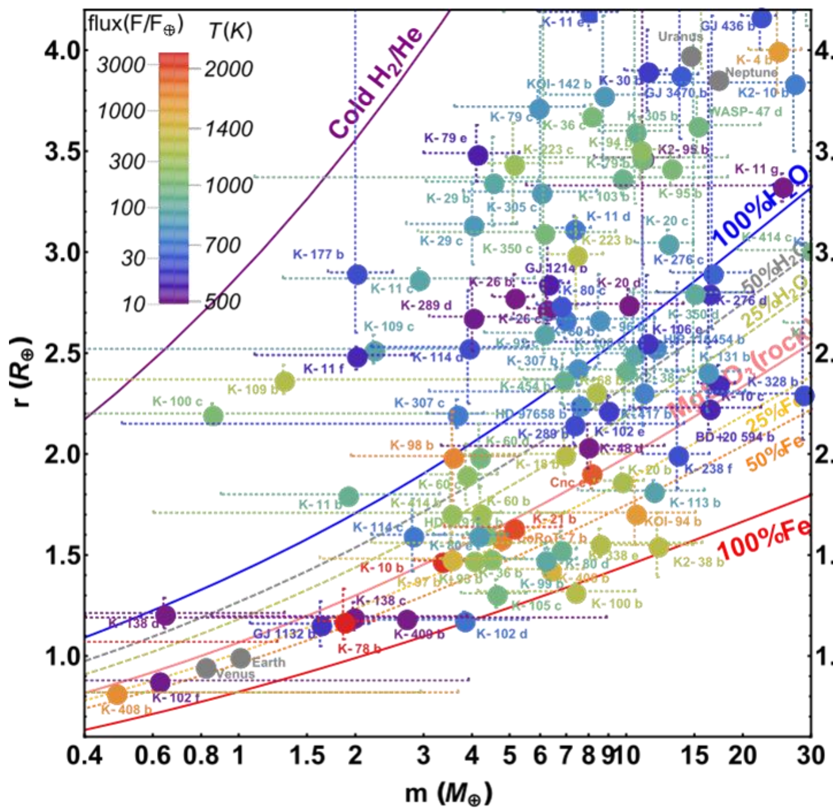
DFG Deutsche Forschungsgemeinschaft

Context: (exo)planetary interiors

Mass & Radius -> mean density

Need of additional observables: the Love numbers h_2 and k_2 [Love, 1911; Kellermann+, 2018, Padovan+, 2018]



[Zeng+, 2016]

The Love number h_2

A planet orbiting a star is subjected to a perturbing potential V_p.

V_p is usually expressed a sum of (spherical) harmonics of degree j:

$$V_p = \sum_{j=2}^{\infty} V_{p,j}$$

The resulting surface displacement, d, can also be expressed as:

$$d = \sum_{j=2}^{\infty} d_j$$

The degree-j surface displacement is given by [Love, 1911; Kopal, 1959]:

$$d_j = h_j \frac{V_{p,j}}{g}$$

[Love, 1911]

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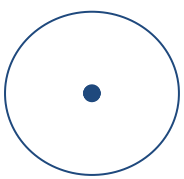
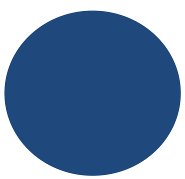
The Love number h_2

Fluid regime	Viscoelastic regime
$h_2 = 1 + k_2$	$h_2 \neq 1 + k_2$
$h_2 = f\big(\rho(r)\big)$	$h_2 = f(\rho(r), \eta(r), \mu(r), \omega)$



$1 \le h_2 \le 2.5$



$0 \le h_2 \le 2.5$

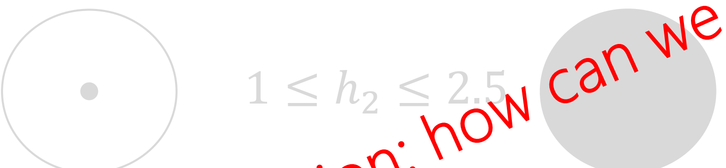
Hot Jupiters

Ice giants, rocky planets

[Love, 1911; Munk & MacDonald, 1960]

The Love number h_2

Fluid regime	Viscoelastic regime
$h_2 = 1 + k_2$	$h_2 \neq 1 + k_2$
$h_2 = f(\rho(r))$	$h_2 = f(\rho(r), \eta(r), \mu(r), \omega)$
$1 \leq h_2 \leq 2.5$	$0 \leq h_2 \leq 1$
Hot Jupiters	Ice giants, rocky planets



Question: how can we measure h_2 of exoplanets ?

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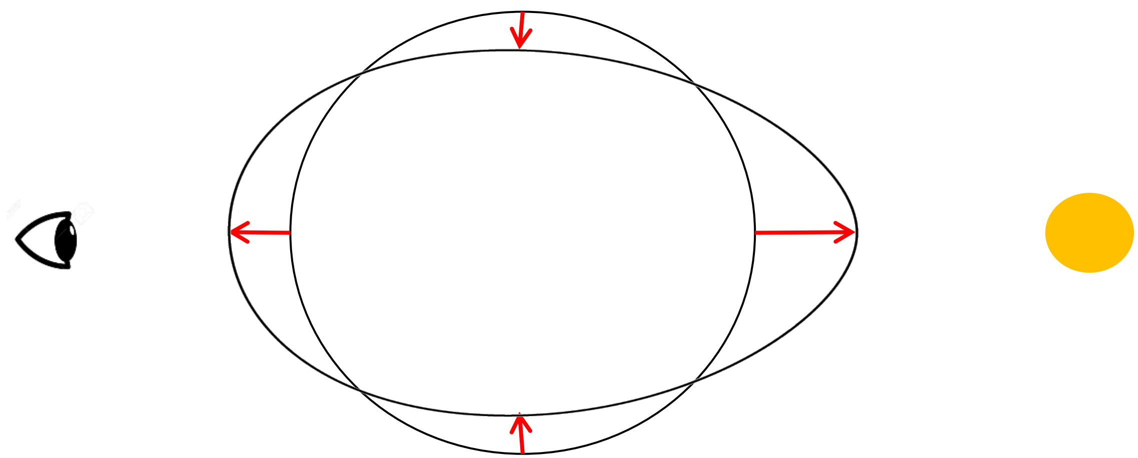
h_2 from transit light curves: modelling the shape

Perturbing potentials: tides & rotation

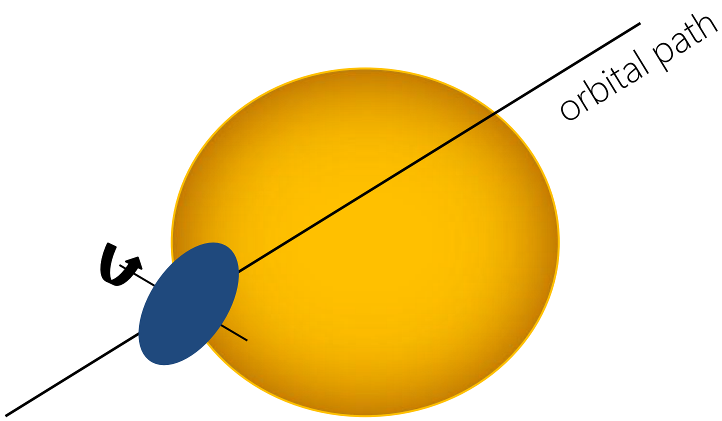


$$r(\theta,\varphi) = R_p\left(1 + \underbrace{q\sum_{j=2}^{4} h_j P_j\left(\frac{R_p}{a}\right)^{j+1}}_{\text{tides}} \underbrace{-\frac{1}{3} h_2 (1+q) F_p^2 \left(\frac{R_p}{a}\right)^{3} P_2(\cos\Theta)}_{\text{rotation}}\right)$$

[Love, 1911; Kopal, 1959]

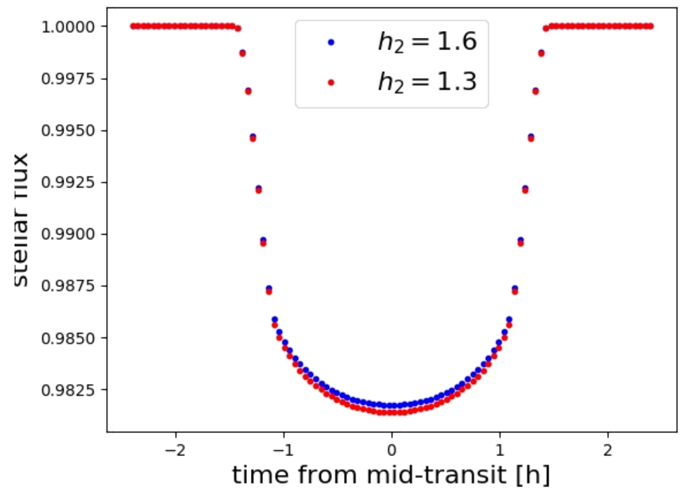
h_2 from transit light curves: modelling the shape

Planetary transit



Transit light curve

Typical hot Jupiter orbiting at ~ 2 Roche radii:



Spherical transiting planet: $h_2 = 0$.

h_2 from transit light curves: feasibility

Hypothetical target: WASP-121b (hot Jupiter)

- stellar limb darkening: quadratic law (u_1, u_2)
  two cases σ_{LDC} = 0.01; 0.005
  (spherical star)
- other parameters a priori unknown
- uncorrelated (white) noise
- Assumed h_2 = 1.5

Parameter (unit)	Assumed value
m_s ($M_\odot$)	1.353
$Vmag$	10.4
u_1	0.3
u_2	0.3
m_p (M_J)	1.184
Inclination (deg)	87.6
Eccentricity	0.0
$\frac{R_p}{R_s}$	0.1313
$\frac{d}{R_s}$	3.7486

To confidently state that the model can measure h2, we require at least a 2σ detection and a relative error $|h_2 - 1.5|/1.5 < 5\%$

[Hellard+, 2019]

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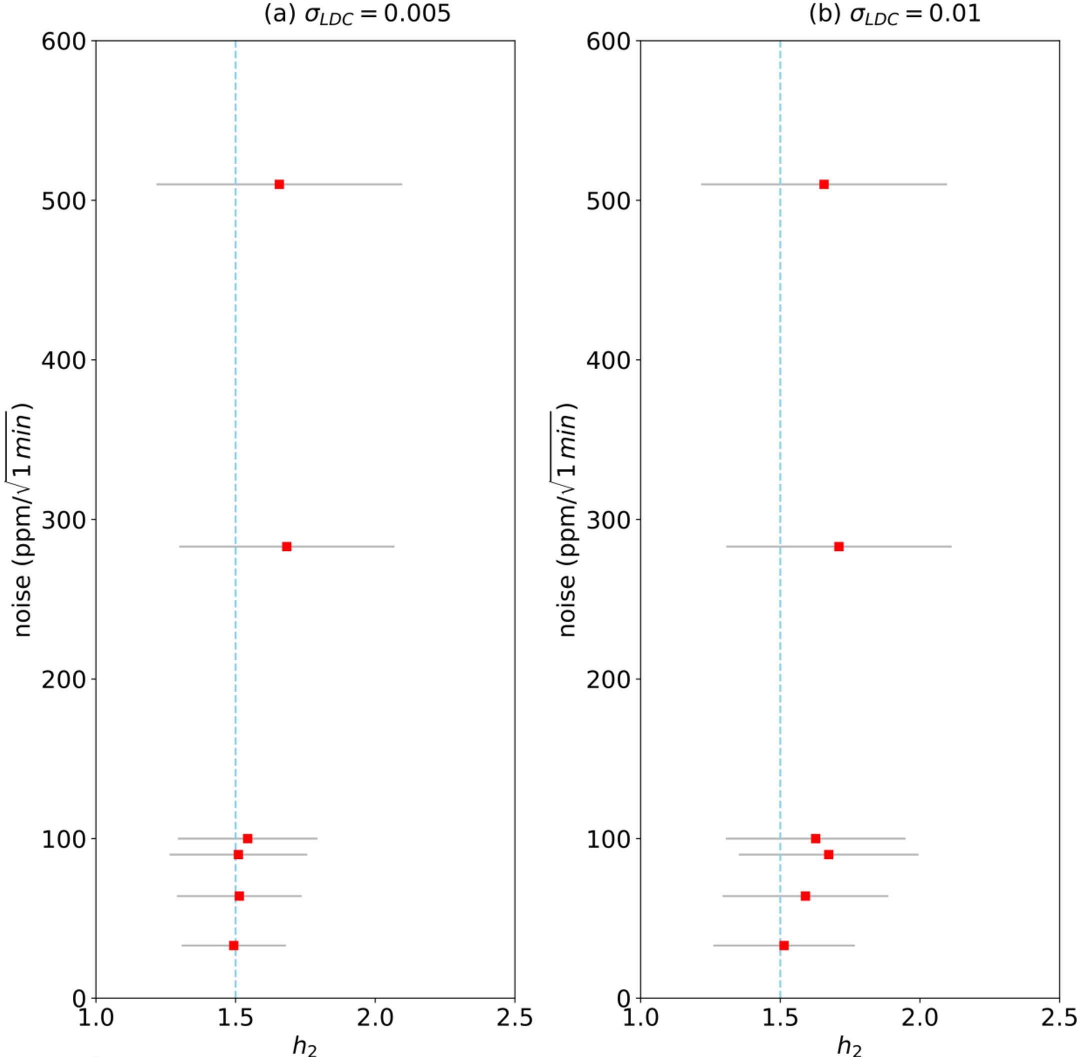
h_2 from transit light curves: feasibility



Precise and accurate measurement of h_2 if [Hellard+, 2019]:

- photometric noise < 90 ppm/min
- σ_{LDC} < 0.01 (yet rarely accessible)

h_2 from transit light curves: feasibility

Precise and accurate measurement of h_2 if [Hellard+, 2019]:

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Results with ellipsoidal shape model [Akinsanmi+, 2019]:

- photometric noise < 50 ppm/min
- σ_{LDC} < 0.01

h_2 from transit light curves: feasibility

What it takes @ 10.4 Vmag:

	Facility	Number of transits to reach 90 ppm/min	Number of transits to reach 50 ppm/min
(2021)	JWST (NIRSpec)	2	4
	Kepler	5	16
(2026)	PLATO	9 (6)	27 (17)
(2019)	CHEOPS	13	40
	TESS	320	1000

Other space-based facilities: HST

Large ground-spaced facilities are also promising, e.g., Gemini, ELT, VLT, LBT.
(but the noise analysis becomes more complex)

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Conclusions

The Love number h_2 provide additional information about (exo)planetary interiors

h_2 can be measured for transiting exoplanets if:

- the photometric uncertainty is < 90 ppm/min
- the stellar limb darkening uncertainty is < 0.01

Hellard, H., Csizmadia, Sz., Padovan, S., et al., 2019. ApJ, 878, 119

h_2 has not yet been measured for any exoplanets ! The best telescopes are still upcoming: JWST, PLATO.

A second Love number, k_2, can be measured from the apsidal motion of (exo)planets in eccentric orbits from their radial velocity and transiting timing observations:

Csizmadia, Sz., Hellard, H., & Smith, A.M.S., 2019. A&A, 623:A45

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Back-up slides

Sensitivity of the Love numbers to the interior

In hot Jupiters, the Love numbers are mostly affected by the outer part of the interior, and not so much by the deep interior.

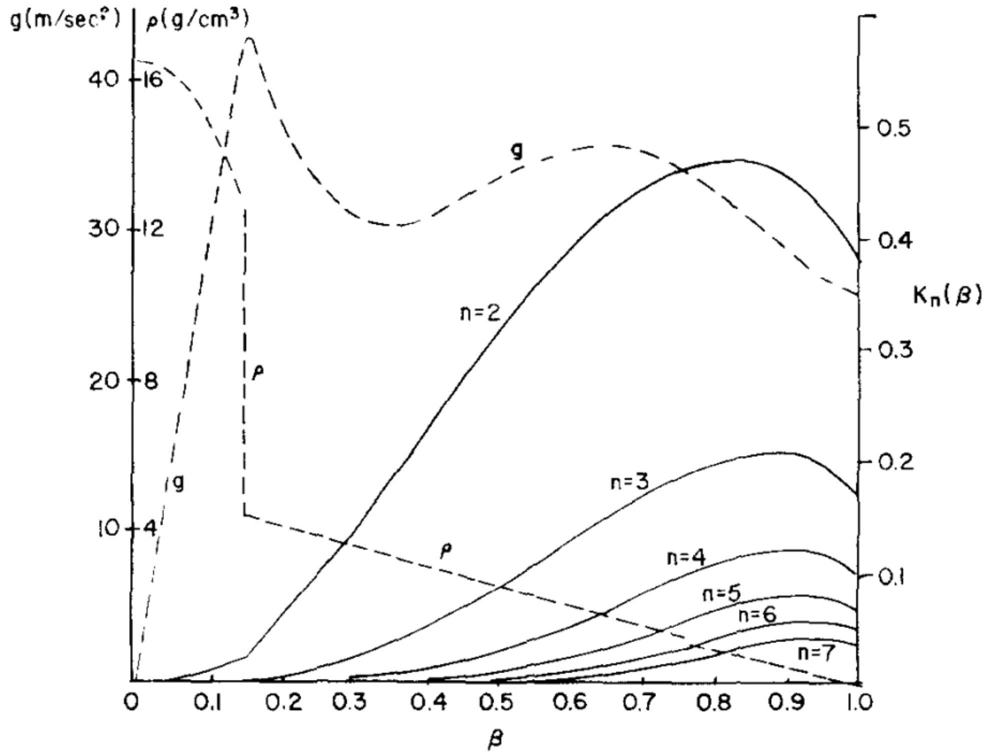
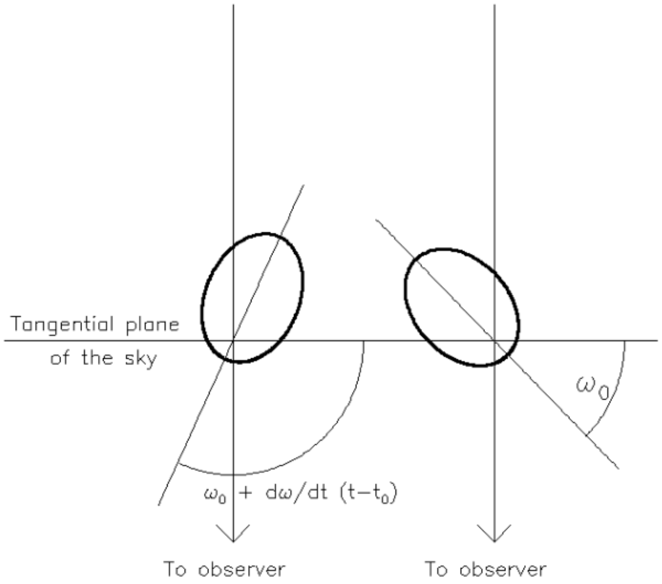


FIG. 1. The Love functions $K_n(\beta)$ of Jupiter, $n = 2$ to 7; ρ and g are the density and the gravity distributions in the planet.

[Gavrilov & Zharkov, 1977]

Apsidal motion of WASP-18Ab

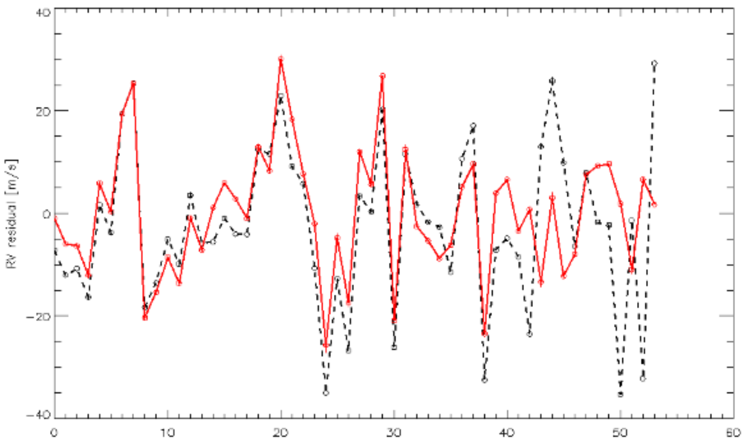
Timescale of apsidal motion ~ 10 – 1000 yrs (i.e. observable)



$$\dot{\omega} = \dot{\omega_{GR}} + \dot{\omega}_t$$
$$\dot{\omega}_t = f(k_2, ..)$$

The apsidal motion will induce:

- Radial velocity variations
- Transit timing variations



Black dashed line: no apsidal motion

Red plain line: apsidal motion

$$k_2 = 0.62^{+0.55}_{-0.19}$$

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